# Development of Inverter Surge Evaluation Technology for Inverter-Driven Motors

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**Abstract**

**In recent years, the trend toward higher voltages and higher frequencies in inverters has led to an increase in the electrical burden on the windings of inverter-driven motors. This electrical burden on the motor windings was evaluated using one-dimensional circuit network analysis and three-dimensional analysis. In addition, the soundness of the actual machine was evaluated by discharge detection using an antenna.**

**One-dimensional analysis showed that a large potential was generated in the windings when a rectangular pulse wave from the inverter was input. The potential of the stator winding was evaluated using the previously described one- dimensional analysis technique and discharge detection. It was evaluated that the potential difference between the turns of the windings is less than the discharge inception voltage. It was also confirmed that no electrical discharge was actually detected.**

## 1 Preface

In recent years, the voltage and frequency of inverters have been increasing along with improvements in the performance of semiconductor elements and control technology used in inverters. Accordingly, the industry is considering the option to increase the efficiency and capacity of inverter-driven motors by increasing the voltage and speed. In particular, higher voltages and higher speeds are required[(1)(2)] for motors used in medium- to large-scale machinery.

However, the higher frequency of inverter carriers and the high-speed switching of main circuit devices cause unique problems. This problem is called "inverter surge" and increases the electrical load on the motor windings. Inverter surge has attracted attention[(3)] as a major problem.

This paper introduces an evaluation of the surge resistance of motor windings, performed using one-dimensional circuit network analysis and three-dimensional electric field analysis.

## 2 Inverter Surge

Inverter-driven motors are known to cause a phenomenon called "inverter surge". Fig. 1 shows an outline of inverter surge. The motor is driven by inputting the pulse wave shown in the center. The surge generated by the operation of the inverter switching element is superimposed on this pulse wave. This surge is amplified as it enters the motor, and the phenomenon in which an overvoltage occurs at the motor terminal is called inverter surge.

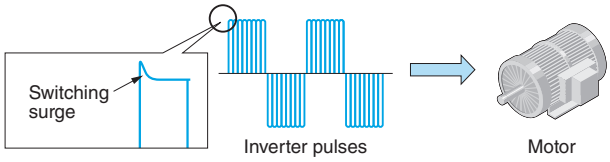



**Fig. 1 Outline of Inverter Surge**

An image of inverter surges is shown, being a challenge to better insulation systems for inverter-driven motors.

In the coils that make up the motor winding, the voltage generated between each turn is normally constant. However, when a surge occurs, the potential distribution within the coil becomes uneven. Then, a potential difference at a level that causes a discharge may occur between the turns. The discharge and deterioration due to this uneven potential difference are major issues.

Here, we would like to evaluate the voltage applied to each coil and turn of the motor due to the

surge. However, it is difficult to measure the actual voltage. Therefore, it is important to perform voltage evaluation using analytical techniques.

## 3 Winding Load Estimation by Analysis

### 3.1 One-Dimensional Analysis

#### 3.1.1 Circuit Network Analysis

We analyze the coil voltage distribution when an impulse wave which simulates a surge intrudes into a winding coil using the one-dimensional network analysis software LTspice.

Fig. 2 shows an outline of one coil and the simplest equivalent circuit. The coil is modeled as a $\pi$-equivalent circuit consisting of inductance and resistance components in the series direction, capacitance, and resistance components between the coil and the iron core.

#### 3.1.2 Circuit Network Analysis Using Experimental Model

Fig. 3 shows the model coil voltage distribution analysis. The model coil made for evaluation was connected and the input potential analysis results and actual measurement results are shown when an impulse wave is input. The circuit parameters for the analysis were measured using an impedance analyzer. The frequency characteristics were measured and appropriate ones were selected according to the surge waveform. In addition, a surge waveform modeled as an exponential waveform is inputted to the circuit software for analysis.

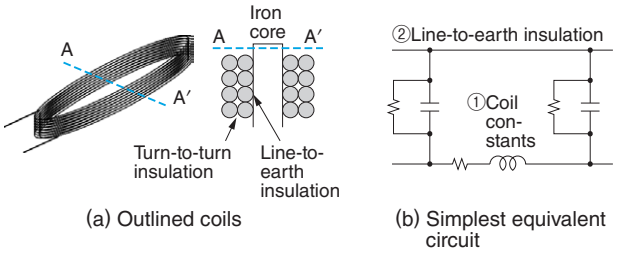
We will explain Fig. 3 (a) shows the circuit with the model coils for evaluation connected in series and the results. (b) shows the circuit with the same number of coils as (a) connected in series and parallel with the analysis results. In both (a) and (b), the analysis and actual measurement waveforms were roughly consistent.

#### 3.1.3 Motor Winding Model Analysis

Fig. 4 shows the circuit analysis results of our product. This is the analysis result when a pulse wave is input to a circuit that models the coils and connections used in an actual motor winding. Note that Fig. 4 shows the coil potential analysis results of several points for one phase of a three-phase connection model.

The input potential of each coil tends to increase with the input pulse. One coil generated a maximum potential 1.6 times that of the input pulse. In addition, there is a phase difference between the input pulses of each coil. Therefore, the potential difference due to the phase difference must also be taken into consideration.

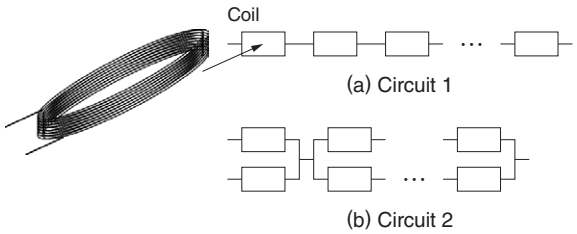
The target motor is a low-voltage class model. Even 1.6 times the input pulse is not a very large potential. Therefore, even if a voltage is applied between the coil turns, it does not exceed the discharge start voltage. It does not reach, and there is no problem with the soundness of the motor winding insulation. However, when a larger surge is superimposed, it is important to suppress it.




(a) Outlined coils (b) Simplest equivalent circuit

**Fig. 2 Equivalent Circuit of Coils**

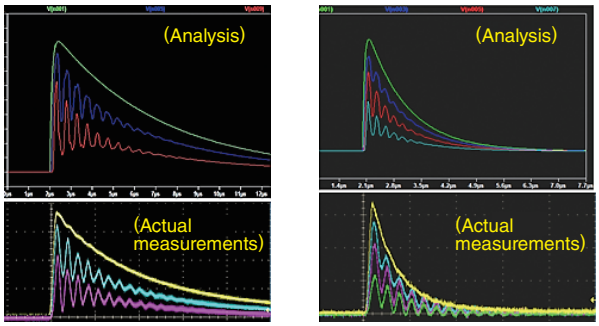
Figures of (a) outlined coils and (b) simplest equivalent circuit are shown.




(a) Circuit 1

(b) Circuit 2

◆Comparison of coil input potentials




(a) Circuit 1: Comparison of analytical result with actual measurements

(b) Circuit 2: Comparison of analytical result with actual measurements

**Fig. 3 Model Coil Voltage Distribution Analysis**

The analytical result of one-dimensional circuit with empirical coils and the result of comparison with actual measurements are shown.

### 3.2 Three-Dimensional Analysis

We performed a field analysis of an actual coil using the coupled analysis software COMSOL. The analysis model was created by 3D scanning the

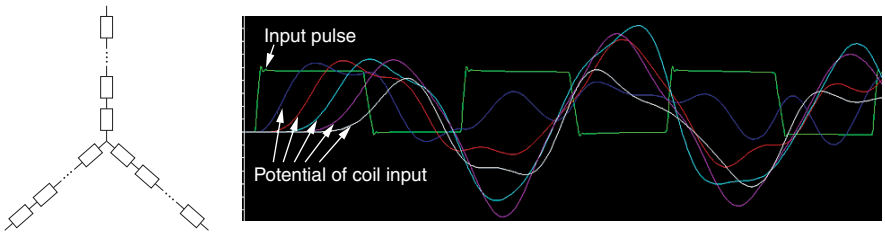



**Fig. 4** Circuit Analysis Results of Our Product

The result of one-dimensional circuit analysis is shown for a case when an input of pulse waves is applied to our product.

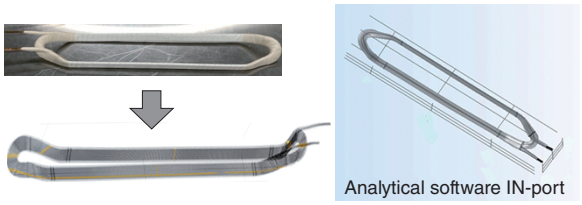
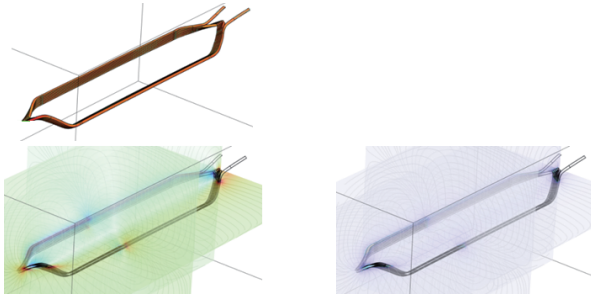



**Fig. 5** Three-Dimensional Model of Coil for Analysis

A coil model for three-dimensional analysis is shown. The model was realized by 3D scanning of actual coils.



(a) Potential (b) Electric field

**Fig. 6** Three-Dimensional Field Analysis of Model Coil

The result of field analysis is shown observed when sinusoidal waves were applied to the model shown in Fig. 5.

coil. Fig. 5 shows the three-dimensional model of the coil for analysis.

Fig. 6 shows the three-dimensional field analysis of the model coil. This time, we performed the analysis using a model without an iron core. From the analysis results, it is expected that the field will concentrate at the coil end.

In this paper, we introduce an analysis example using a sine wave. We have also performed analysis of impulse waves and pulse waves, but there is still room for further study.

## 4 Measurement of Coil Discharges

### 4.1 Model Coil Discharge Inception Voltage

To evaluate the soundness of motor winding

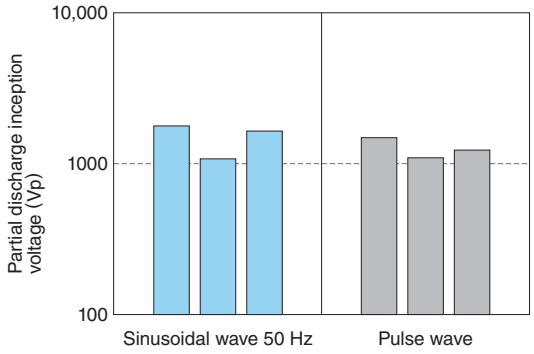



**Fig. 7** Partial Discharge Inception Voltage between Model Coil Turns

The result of measurement is shown for the partial discharge inception voltage applied among model coil turns. No great difference was perceived between the peak value of sinusoidal waves and pulse waves.

insulation, it is necessary to measure the actual discharge inception voltage in addition to the voltage shared by each coil.

Fig. 7 shows the partial discharge inception voltage between model coil turns. The discharge inception voltage when a commercial frequency sinusoidal wave and a high-frequency pulse wave are input between the coil turns is compared. Here, for the commercial frequency sinusoidal wave, the discharge is measured by the detection impedance method. When a partial discharge occurs, a pulse current flows. The detection impedance method is a method of detecting this pulse current with a coupling capacitor and a resistor. In this evaluation test, the discharge charge amount is set to 10 pC as the standard, and the judgment is made by the partial discharge inception voltage measurement function of the measuring device.

On the other hand, in the case of a pulse wave, the frequency of the partial discharge generated is high frequency. For this reason, measurement by the detection impedance method is difficult. Here, the discharge was detected by the electromagnetic wave method, which detects the radiated electro-

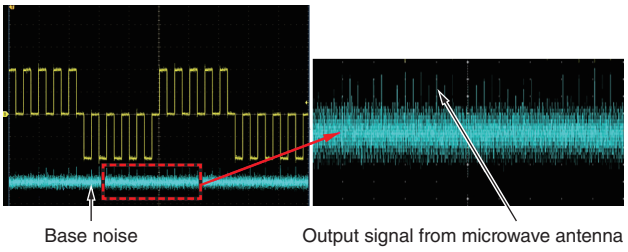



**Fig. 8** A View of Partial Discharge Detection Using Ultra-High Frequency Antenna

A View of partial discharge detection using the microwave antenna is shown.

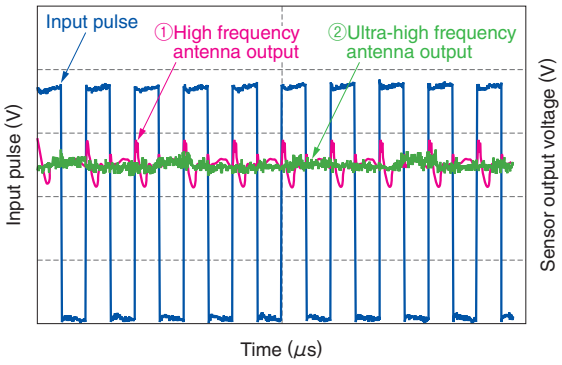



**Fig. 9** Stator Discharge Detection

Stator discharge detection was carried out when an input of pulse waves was applied to the motor stator of trial production. For this objective model, no partial discharges were generated when a driving voltage and frequency were applied.

magnetic waves generated by the partial discharge with an antenna. In this evaluation test, an antenna with high sensitivity in the short wave and ultra-high frequency bands was used. Fig. 8 shows the partial discharge detection using the ultra-high frequency antenna. The voltage value when the output signal of the antenna is clearly larger than the base noise signal is taken as the discharge inception voltage. In this test, the discharge inception voltage (peak value) of both the maximum sine wave and the pulse signal was 1000 Vp or more, and it can be evaluated that there is almost no difference.

### 4.2 Stator Discharge Measurement

A pulse signal with a frequency of 10 kHz and a rise time of 100 ns was input to the motor stator manufactured for evaluation, and discharge measurement was performed at that time. Fig. 9 shows the stator discharge detection. Discharge measurement was performed using three methods. The discharge radiation electromagnetic wave measurement (① high frequency antenna −3 MHz to 30 MHz, ② ultra-high frequency antenna −300 MHz to 3 GHz), and transient earth voltage measurement (③ Transient Earth Voltage 〈TEV〉 sensor-same frequency band as the shortwave antenna). This prototype is wired with the model coil described in **Section 4.1**. The TEV sensor was largely affected by noise because no countermeasures were taken, and the results in Fig. 9 are omitted.

Fig. 9 shows that the high frequency antenna reacts at the rising edge of the input pulse. The ultra-high frequency antenna did not obtain a signal at a level that could be clearly distinguished from the base noise shown in Fig. 8.

Here, a circuit analysis similar to that in **Section 3.1.3** was performed on the stator that is the subject of this section. According to the results of the circuit analysis, no voltage is generated between the stator coils that exceeds the partial discharge inception shown in Fig. 8. When the driving voltage and frequency are applied, no discharge occurs, and it is evaluated that the motor winding insulation maintains its integrity.

## 5 Postscript

The electrical load on the motor windings was evaluated using one-dimensional circuit network analysis and three-dimensional field analysis. Discharge measurements were also performed when voltage was applied to the coil and stator.

Going forward, we will continue to estimate the electrical load more accurately and consider countermeasures.

We will continue to devote our efforts to technological development and motor insulation evaluation in order to provide our customers with high-quality motor insulation.


- LTspice is the registered trademark of Analog Devices, Inc.
- COMSOL is the registered trademark of COMSOL AB.
- All product and company names mentioned in this paper are the trademarks and/or service marks of their respective owners.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